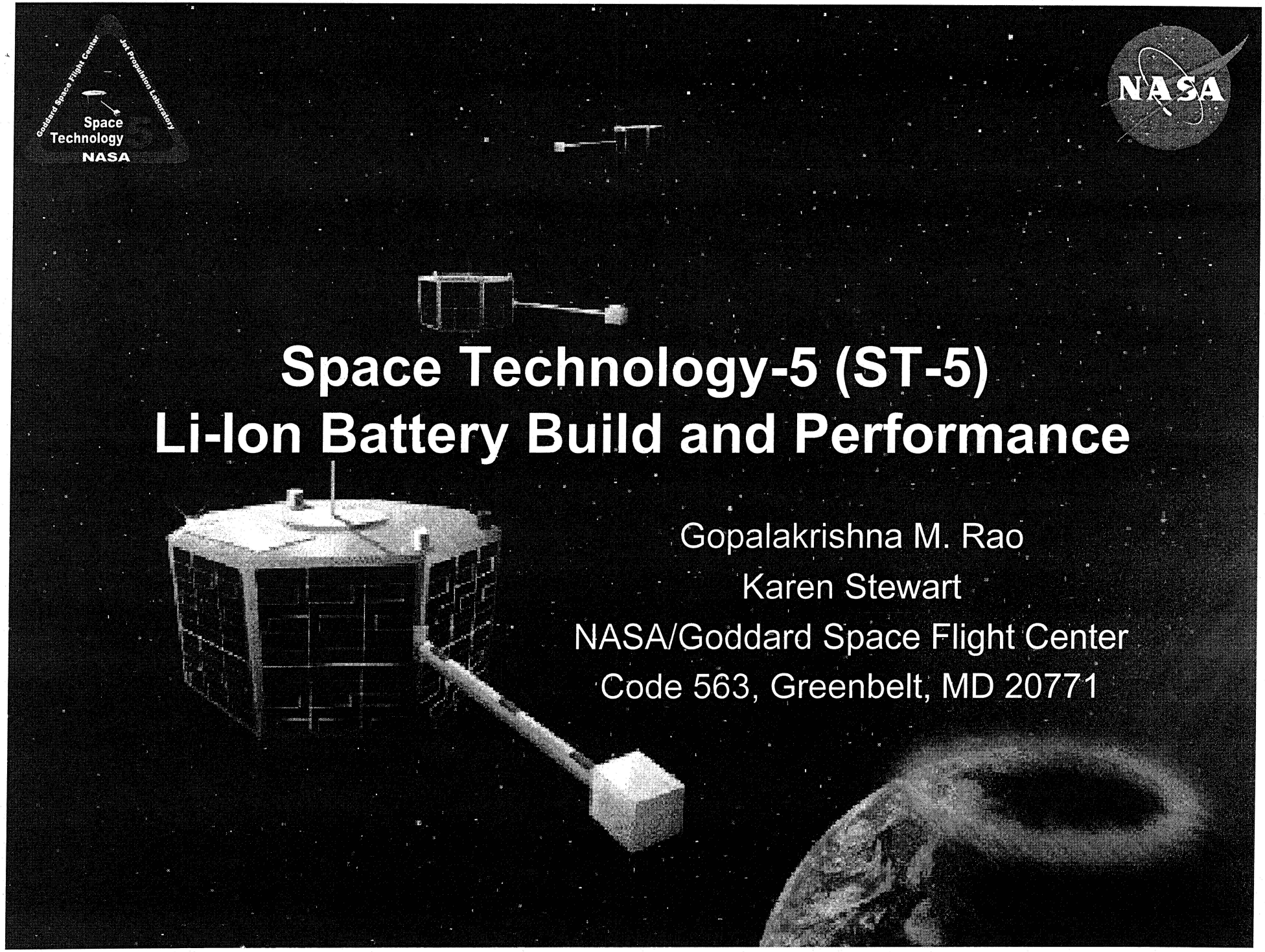

Space Technology-5 (ST-5) Li-Ion Battery Build and Performance

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Karen Stewart
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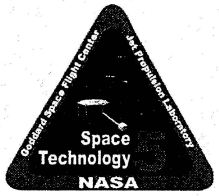
Code 563, Greenbelt, MD 20771



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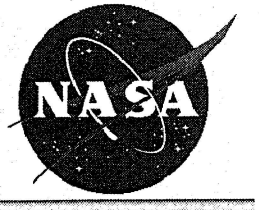
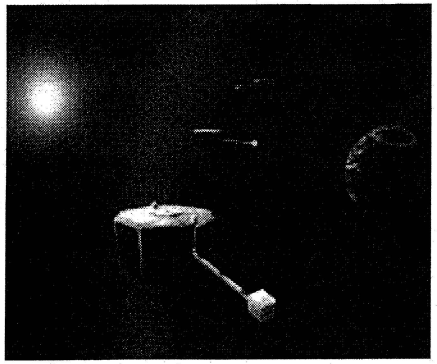
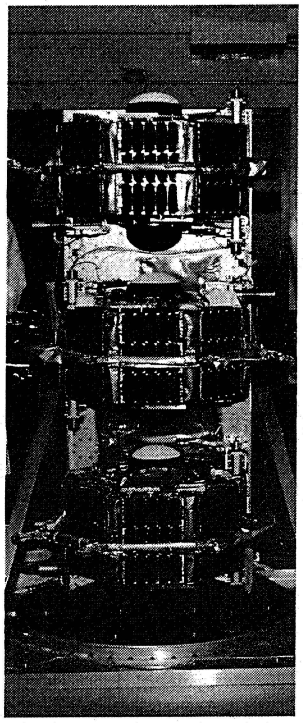


- Mission Overview
- Power System Features
- Li-Ion Battery
  - Specification
  - Requirements
  - Design
  - Qualification and Acceptance
  - In Orbit Performance
- Summary and Conclusions

Space Technology-5 Mission Overview

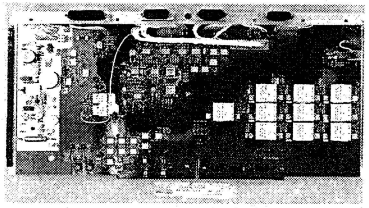
- A New Technology Mission to further investigate Space Weather and to validate new technologies for future use in space
  - Lithium-Ion battery,
  - Cold Gas Micro-Thruster,
  - Variable EmittanceThermal Coatings,
  - Ultra Low Power Logic,
  - Miniature Transponder,
  - Autonomous Ground System Software
- A 3-satellite constellation
- Launched on March 22, 2006 from Vandenberg AFB
- Polar elliptical, Sun synchronous orbit
- Octagonal spinning satellites

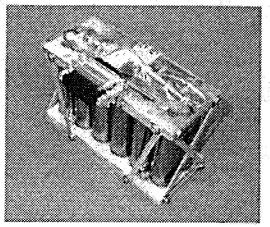


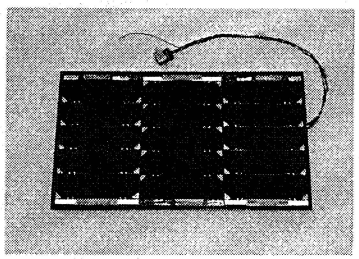


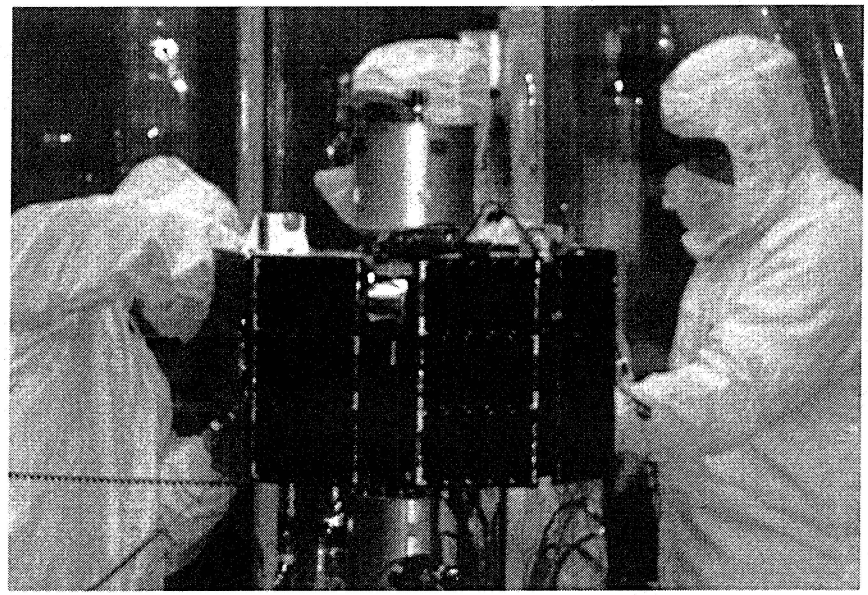
Power System Features

- Low Voltage Power Bus to maximize power efficiency
- Miniature Power System Electronics (PSE)
- High efficiency solar cells-- Triple Junction GaAs solar cells, 28.5% efficient
- High energy density battery – Lithium-Ion
  - About 3-fold increase in energy density compared with current battery chemistries.



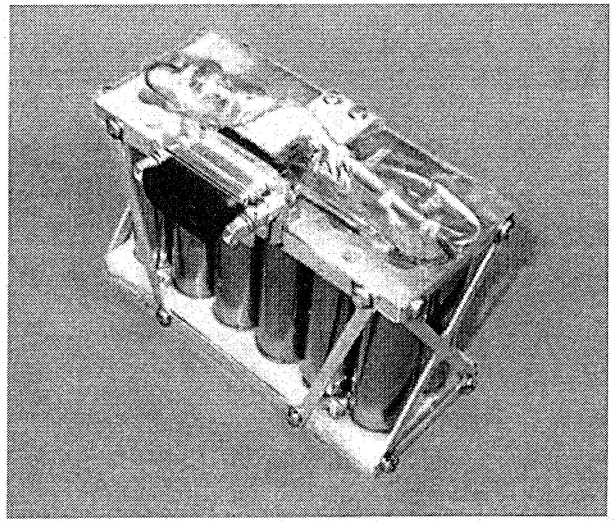


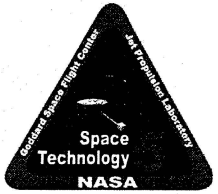




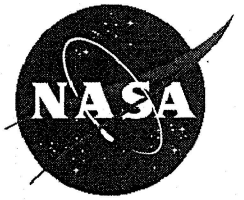
Li-Ion Battery Specification

- **Battery Voltage Limits**:
  - Maximum End-of-Charge Voltage 8.4 V
  - Minimum End-of-Discharge Voltage 5.0 V
- **Battery Capacity (C):** 7.5 Ah
- **Battery Energy:** 54 Wh
- **Minimum Voltage after Peak Load:** 6.0 V
- **Battery Self Discharge**: <=8% per month
- **Charge retention after 72 hrs of open circuit** > 0.98*C
- **Charge Management:**
  - Constant current charge (C/5) to voltage clamp at the battery level
- **Charge Capability**: Max charge rate of 1C
- **Impedance:** < 90 mΩ





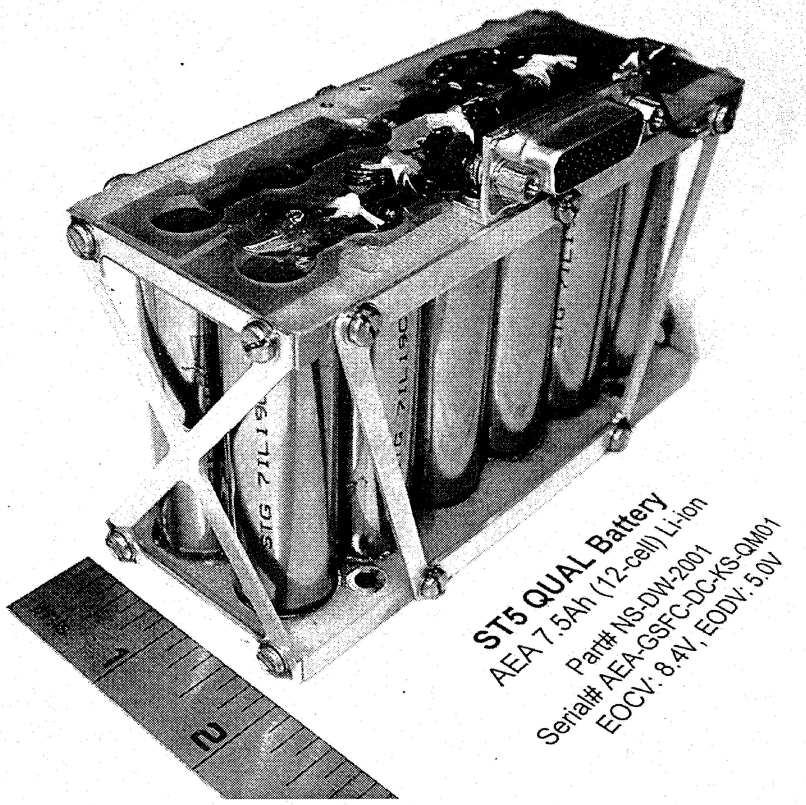
Li-Ion Battery Requirements



- Orbit:
  - Original: Geo Transfer Orbit
  - Changed to: Polar elliptical orbit, sun synchronous (due to LV change)
    - 2.27 hrs Orbit Period (seasonal eclipses up to 22 minutes)
- Mission Phases:
  - Storage: 3 Years
  - Ground Test: 100 cycles
  - Mission Life: 3 months requirement with a goal of 6 months
- Operating Temperature Range:
  - -10 to 40°C
- Charge / Discharge
  - Ground: 3 years, 100 cycles @ 100% DoD
  - Flight: (Approximately six months) 400 cycles @ 60% Depth of Discharge
- Max. Discharge load: 12 W
- Discharge Capability:
  - 12 W for 22 mins and 14 W for 15 mins during eclipse season

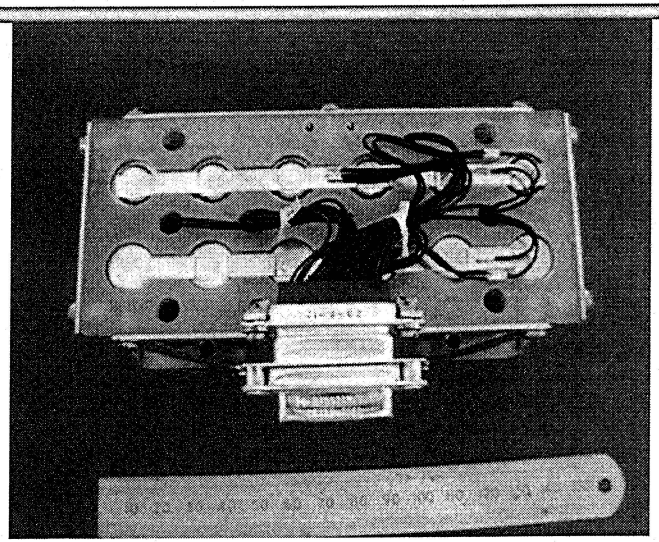
Lithium-Ion Battery: Design

- AEA (now ABSL Space Products) assembled battery using twelve individual SONY 18650 1.5 Ah cells
- Arranged in a Series-Parallel system topology
- 6 parallel strings, 7.5Ah virtual cell at 20°C
- 2 virtual cells in series string provide battery voltage (6 to 8.4 V)
- Cells have built in safety features that improve reliability over larger size Lithium-Ion cells and could eliminate cell bypass electronics

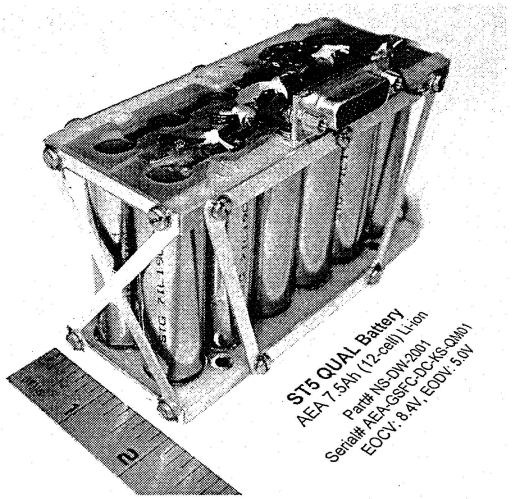


Li-Ion Battery: Mechanical Design

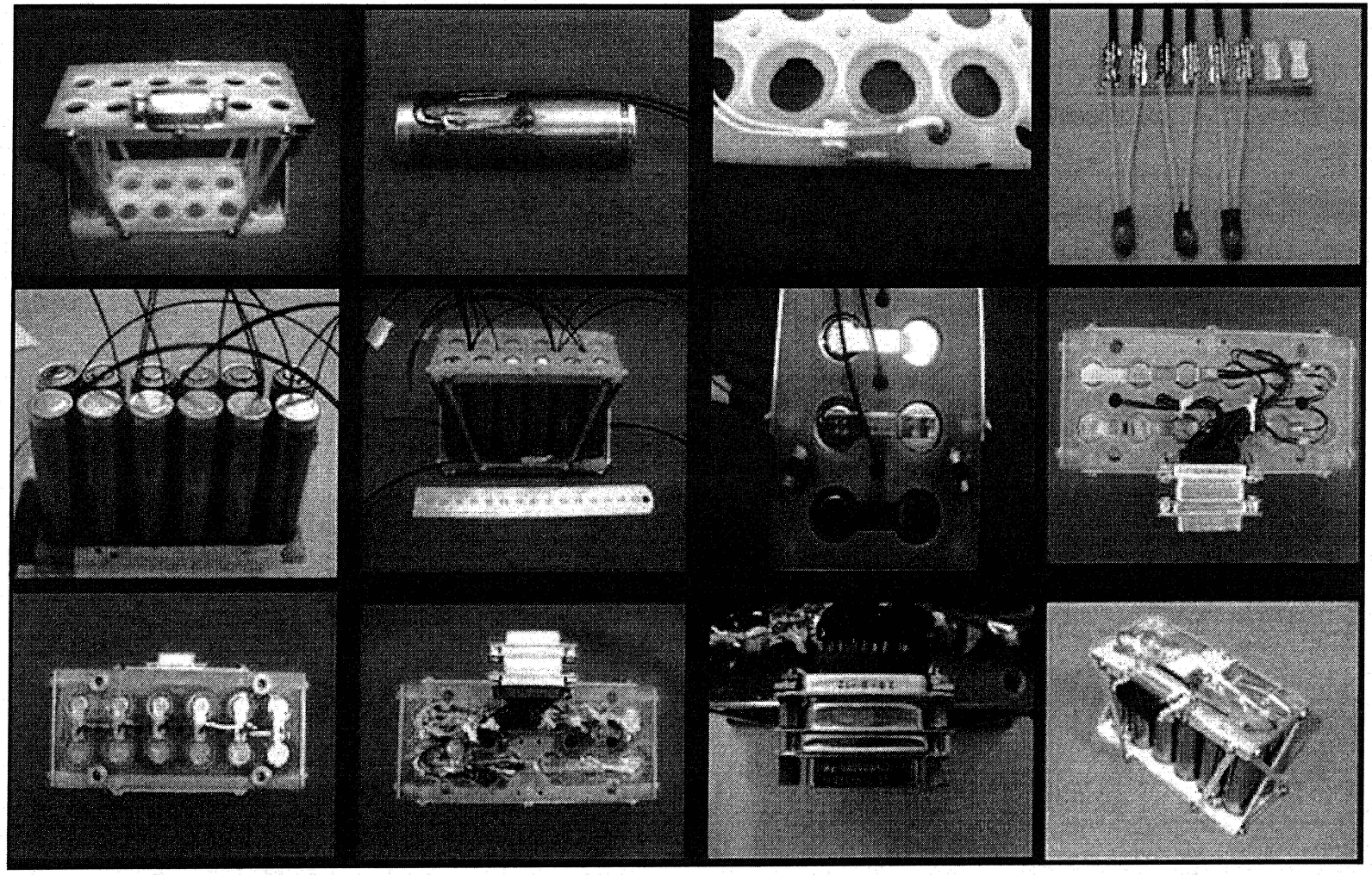
- Tray assembly using two sheets of Glass Fiber Reinforced Plastic (GFRP)
- Isotropic high strength, electrical isolator & low density material
- Provides a structure that is highly rigid, high bending resistance
- Shear rigidity provided by cross bracing using thin aluminium sheet
- Interconnects between cells pre-formed (provides stress relief)
- Four separate spot welds using robotic spot welder.



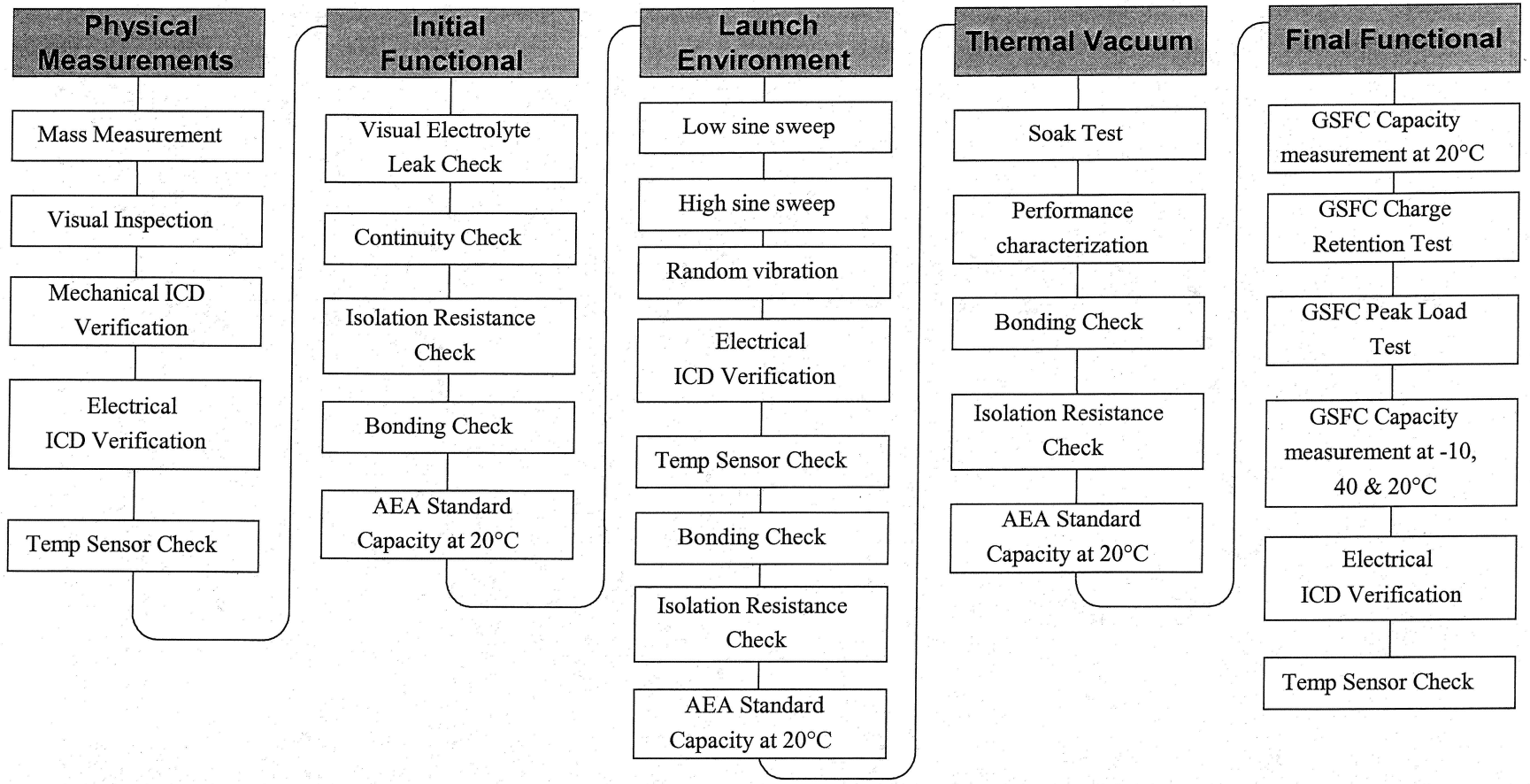
Dimensions: 12.4 cm x 6.3 cm x 8.6 cm
Mass: 0.643 Kg



Li-Ion Battery: Design-- continued

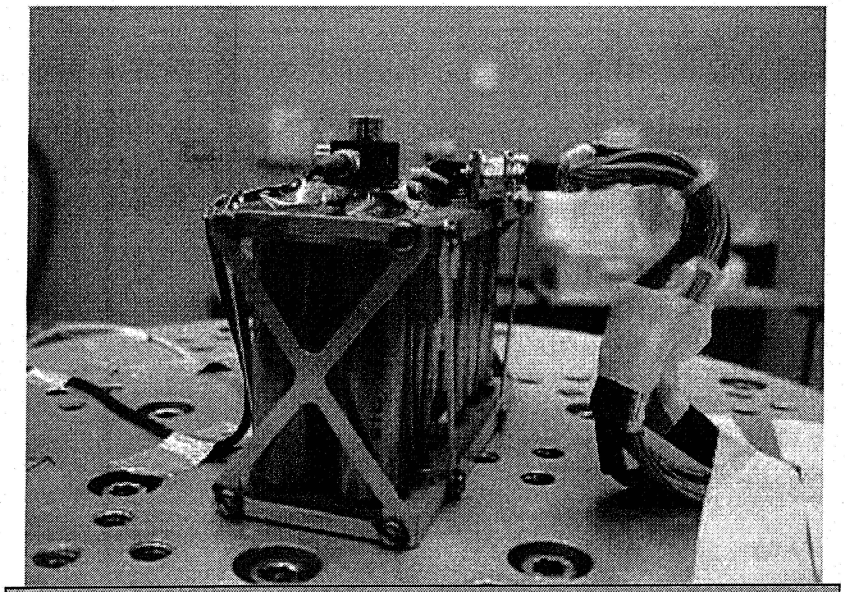


Li-Ion Battery: Qualification/Acceptance Plans

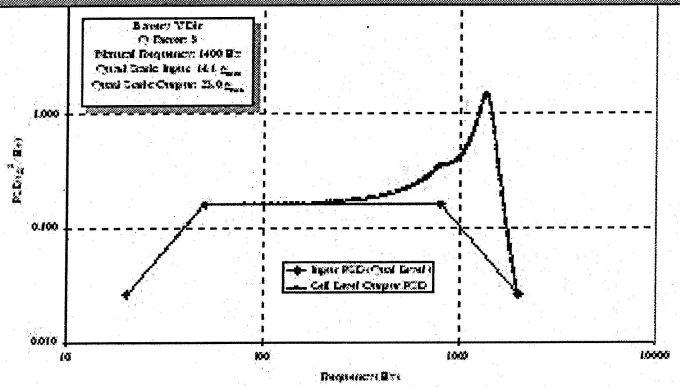


Identical flow of tests for both Qualification & Acceptance program, but testing at appropriate levels.

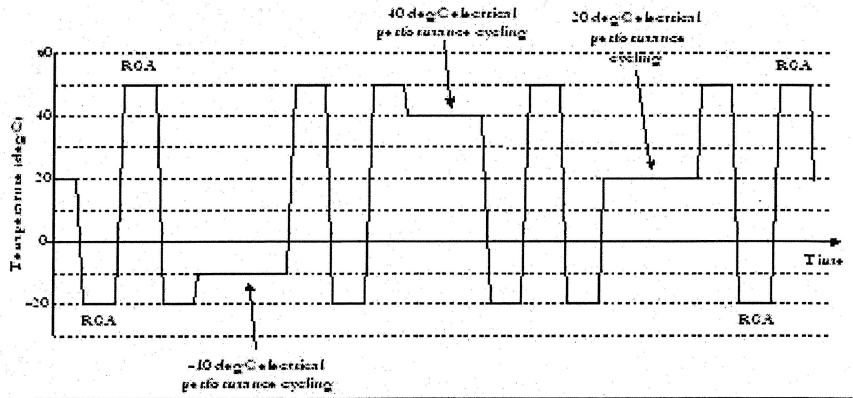
Li-Ion Battery: Qualification-Environmental Testing

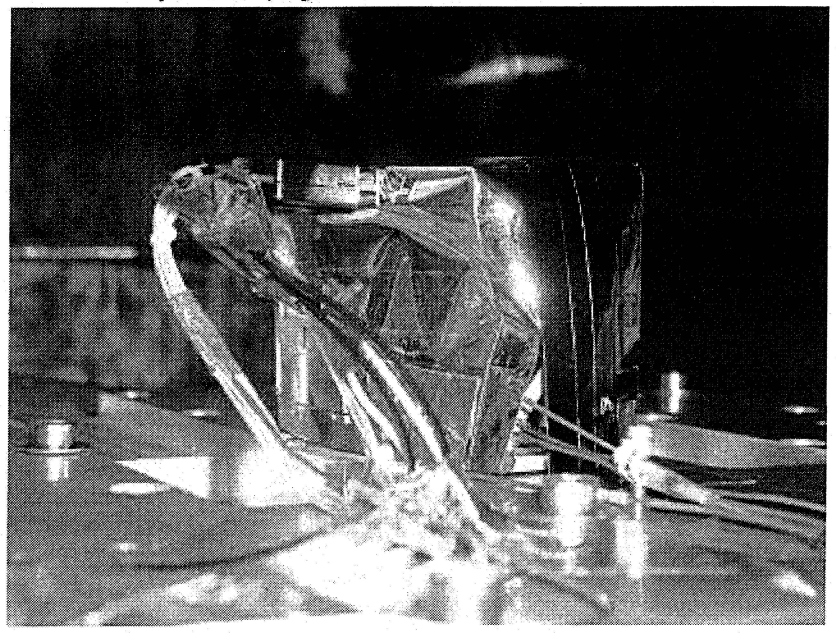


Vibration levels for Qualification



Thermal vacuum profile for Qualification





Li-Ion Battery: Qualification/Acceptance Data

Physical & Functional Test			
Mass		*0.643 Kg*	
Dimension: L x W x H (cm)		*12.35 x 6.26 x 8.55*	
Battery Voltage (0%SoC)		*5.92V*	
Electrolyte Leak Check		*No leak*	
Isolation		*> 100 MΩ*	
Bonding		*< 9.5 mΩ max.*	
Thermistor Resistance			
TH01	**TH02**	**TH03**	**TH04**
2.50 KΩ	*2.50 KΩ*	*2.49 KΩ*	*2.50 KΩ*

Capacity Measurement		
AEA SCM (C/10 Discharge)		
SCM #1 (Pre-Vibration)	**SCM #2 (Post-Vibration)**	**SCM #3 (Post-Charge Retention)**
8.56 Ah	*8.48 Ah*	*8.32 Ah*

GSFC SCM (C/2 Discharge)			
1st 20°C	**-10°C**	**40°C**	**2nd 20°C**
7.67 Ah	*6.68 Ah*	*7.81 Ah*	*7.60 Ah*

Vibration Test			
Axis	**Resonance**	**Peak G_{rms}**	**Q Factor**
X	*974 Hz*	*33.8 g*	*10.9*
Y	*1034 Hz*	*27.6 g*	*6.4*
Z	*> 2000 Hz*	*14.2 g*	*1.2*

Batteries passed all Qualification and Acceptance Testing.

Li-Ion Battery: Qualification/Acceptance Data – contd.

Peak Load Test	
EoD V	*> 7V*

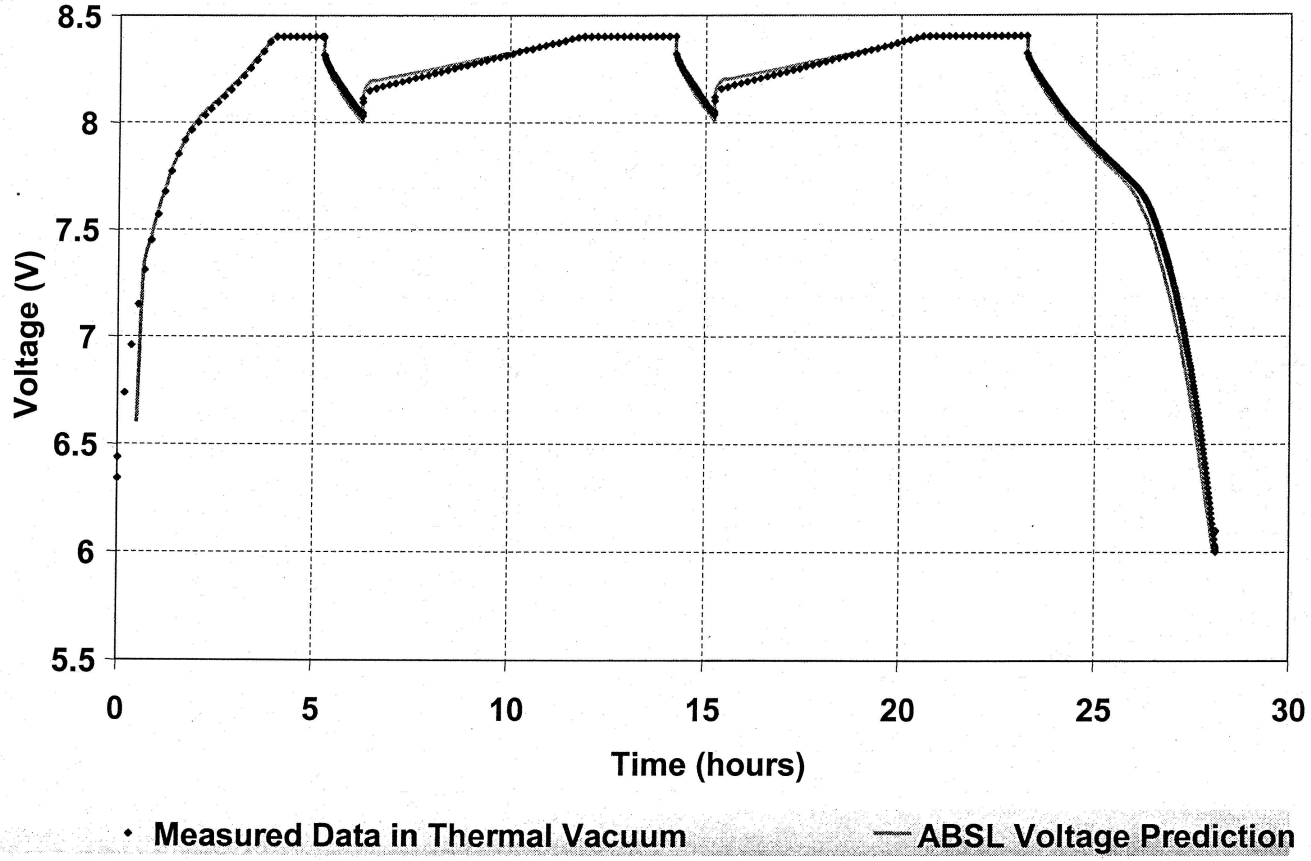
Thermal Vacuum Test			
Thermal Cycle Test			
No. of Thermal Cycles	*3*		
Max. Temperature	*40°C*		
Min. Temperature	*-10°C*		
Performance Cycle Test			
No. of Performance Cycles	3		
Temperature	**EoDV (12W for 60 min)**		
	Cycle 1	**Cycle 2**	**Cycle 3**
40°C	*8.07 V*	*8.08 V*	*8.08 V*
-10°C	*7.86 V*	*7.85 V*	*7.84 V*
Residual Gas Analyzer (RGA) Monitor (leak check)			
Mass Number Range	*1 to 100*		
Electrolyte Trace	*No*		

Final Functional Test			
Charge Retention	*98.14%*		
Electrolyte Leak Check	*No leak*		
Isolation	*> 100 MΩ*		
Bonding	*22.3 mΩ*		
Battery Voltage (0%SoC)	*5.71 V*		
Thermistor Resistance			
TH01	**TH02**	**TH03**	**TH04**
2.34 kΩ	*2.33 kΩ*	*2.31 kΩ*	*2.32 kΩ*

Performance of Flight Batteries and Flight Spare were within expected nominal tolerance range.

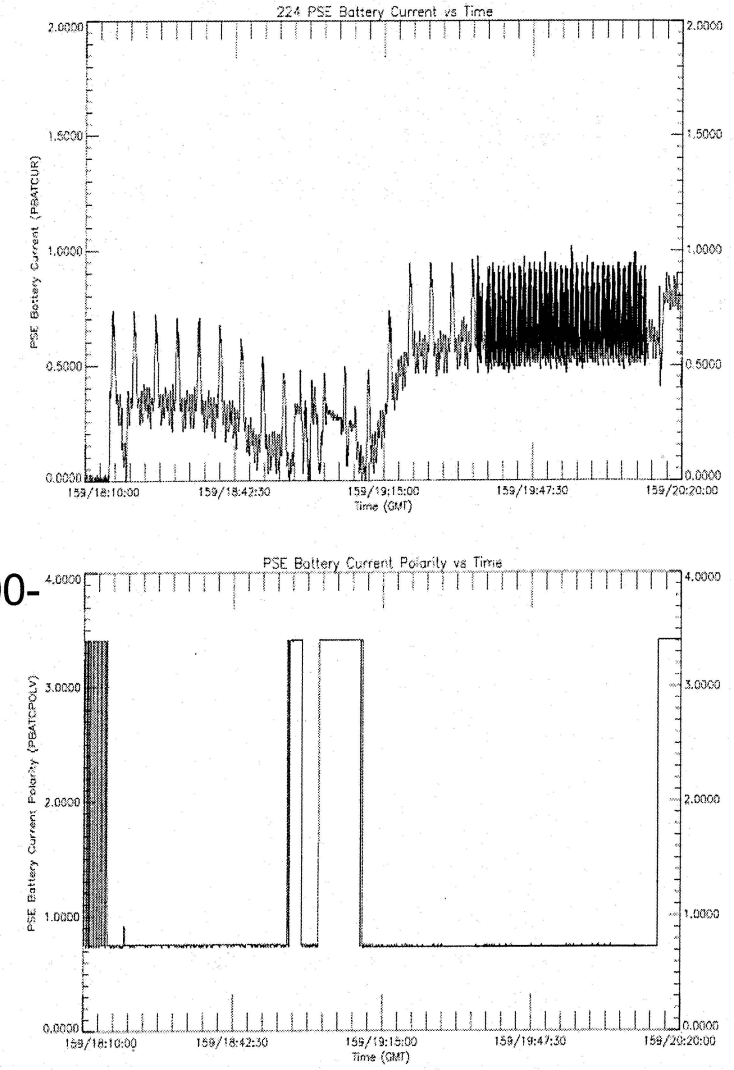
Li-Ion Battery: Thermal Vac

- Voltage measurements in thermal vacuum shows excellent correlation both at 15% DoD and when fully discharged to 6 V at 12W.



Li-Ion Battery: In-Orbit Performance

- Launched on March 22, 2006
- Over the 3 month mission life, each of the 3 batteries experienced:
- Approximately 100 cycles on orbit, 2-5% DoD*
  - Includes long discharge periods, 90-120 minutes in length
  - No noticeable degradation or capacity fade
    - Battery voltage recovered quickly after long, 90-120 minute discharges

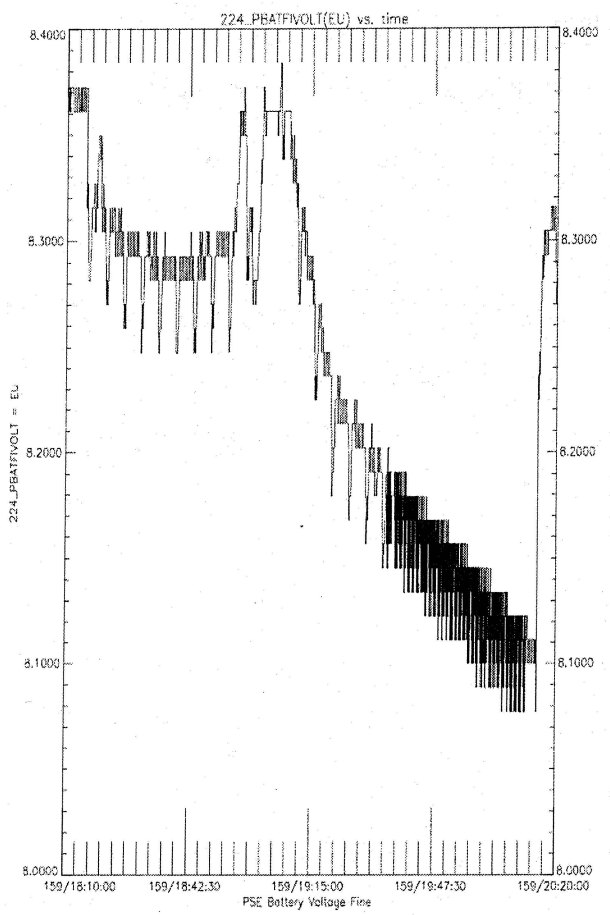


Battery Current Magnitude and Polarity during 120 minute discharge

*Original DoD of 60% was specified due to original GTO orbit. New orbit, sun synchronous polar orbit, requires DoD of <10%.

Li-Ion Battery: In-Orbit Performance—contd.

- Battery Voltage during long, 120 minute discharge, shows quick voltage recovery at end of discharge*

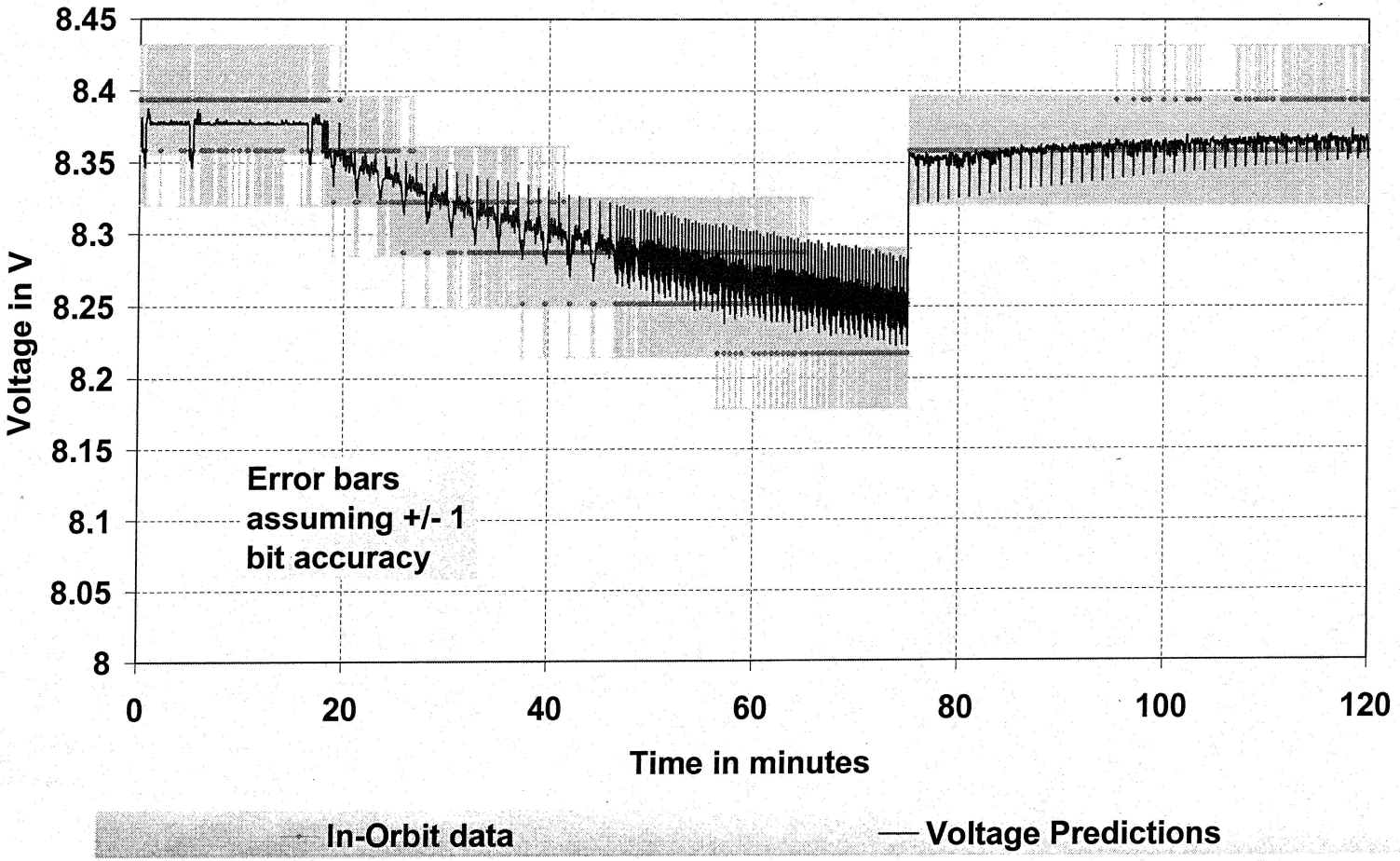


Battery Voltage during 120 minute discharge and recovery

* 120 minute discharges, at rates of C/10-C/20 Ah, were performed in sunlight during required spacecraft ground contacts.

Li-Ion Battery: ABSL Predicted Voltage versus Flight Performance

- Correlation is good but could improve with higher resolution telemetry and deeper battery discharge.



Summary and Conclusions

- Lithium-Ion battery technology qualified for space on ST-5 mission
  - AEA (now ABSL Space Products) built, Qualification/Acceptance tested and delivered ST-5 batteries
- Batteries were stored for 32 months prior to launch in March 2006
  - Capacity fade after long storage was minimal (less than 4%)
  - Performance better than predicted after long storage
- Flight battery performance nominal throughout the 90-day mission
  - Expected performance correlated with the ABSL performance prediction
- Lithium-Ion technology has been successfully flown on ST-5 (03/2006), CALIPSO (04/2006) and THEMIS (02/2007)
  - ST-5 served as a precursor/pathfinder for a 28V, 20Ah battery that lead to designs for THEMIS, SDO and LRO batteries.
- Goddard Space Flight Center has baselined Li-Ion batteries for SDO (ABSL), LRO (ABSL), IBEX (Yardney), GPM (TBD) and MMS (TBD) spacecraft.
  - SDO and LRO are the largest of the ABSL batteries ever built for space
- The lessons learned from our 3+ years of real-time life cycle testing on all potential aerospace cell/battery vendors, together with ST-5, CALIPSO and THEMIS flight experience, will be implemented in the future cell/battery designs, battery ground handling and on board battery management.
  - Lessons learned also include appropriate handling plans, launch site operations, operational plans and procedures, charging methods to extend life, performance of cells, de-orbit operations.